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SYSTEMATIC ERRORS IN OPERATIONAL BAROCLINIC PROGNOSES AT THE NATIONAL METEOROLOGICAL CENTER

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ABSTRACT

This paper reviews the performance of the short-range, operational national weather prediction over the Northern Hemisphere at the National Meteorological Center. Mean monthly 500-mb error charts, valid at 1200 GMT only, for four midseason months of 1964 through 1968 are presented from 36-hr prognoses made using the National Meteorological Center's operational three-level and primitive equation models. Systematic errors found to persist in both models show that, in the mean, the amplitude of troughs and ridges is underforecast. This tendency shows up in mean monthly and in daily error charts as positive errors in troughs and negative errors in ridges. Very large-scale errors (i.e., in waves 1 through 5 and so on when used in this context) occur in forecasts from both models. The causes of these very large-scale errors remains obscure. However, the causes of certain smaller scale systematic errors have been diagnosed. In particular, the large 500-mb negative error over western Canada, ahead of the Gulf of Alaska trough, has been diagnosed as caused by deficiencies in amplitude of the terrain in the models over western Canada. Corrective adjustments in the model mountains made in September 1968 have decreased errors over western Canada. Comparison of errors in the three-level and later primitive equation 500-mb prognoses indicates that an improvement in skill has occurred over North America. Preliminary study of the vertical distribution of errors from 1000 mb to 200 mb in September and October 1968 indicates that the primitive equation model 1) underforecasts the strength of the mean thermal wind particularly above 500 mb, and 2) contains a negative bias in the depth of 1000 mb (surface) Lows east of the American Rockies.

1. INTRODUCTION

The improvement in operational forecast performance over North America at the National Meteorological Center (NMC) realized through exploitation of first the barotropic, then the three-level, and recently the primitive equation (PE) model has been well documented by Shuman and Hovermale (1968). This paper examines the average performance around the Northern Hemisphere over a 5-yr period of the NMC three-level and PE models, and relates this performance to the macro structure of hemispheric flow patterns. One of the longest continuous records of performance of an operational numerical weather prediction (NWP) forecast system is discussed and is used to present an assessment of the state of the art in the United States of operational numerical prediction.

Since August 1964, monthly averaged 36-hr errors of the NMC 500-mb baroclinic prongnoses, valid at 1200 GMT *only*, and the corresponding averaged 1200 GMT *observed* 500-mb heights have been tabulated (forecast verifications by the NWP Group, NMC, Suitland, Md.) for the grid points circled in figure 1. The 500-mb heights and errors have been plotted on hemispheric charts and analyzed by hand. The mean positions of the 500-mb jets have also been entered from inspection of the contour spacing on the mean charts.

Beginning in September 1968, mean monthly 36-hr heights and errors for the NMC baroclinic prognoses have been tabulated for the 1000-mb, 850-mb, 300-mb, and 200-mb prognoses as well as for the 500-mb prognosis, valid at 1200 GMT.

SIGNIFICANT DATES

Knowledge of dates of significant changes in type or structure of models used at NMC is necessary to evaluate the error charts.

May 1966. The last month in which the Cressman three-level filtered model (1963), hereafter referred to as the three-level model, was in operation at NMC.

June 1966. The NMC six-layer primitive equation model (Shuman and Hovermale, 1968), hereafter referred to as the PE model, was placed in operation.

February 1967. Use of latent heat feedback began in the PE model (Shuman and Hovermale, 1968).

September 1968. Use of rough mountains began over western North America (Weather Analysis and Prediction Division, 1968) in the PE model.

Several other physical and programming adjustments have been made since 1966 in the PE model. However, only those changes listed are considered significant in evaluation of the large-scale errors which predominate, after the daily charts and errors are time averaged to obtain monthly means.

A representative selection of 16 mean monthly error charts is included (figs. 2–5). For each season, there is a set of four monthly charts (1A, B, C, D, etc.). January, April, July, and October charts were selected to represent each of the four seasons. Two sets of *four* error charts for September and October 1968 are included in figures

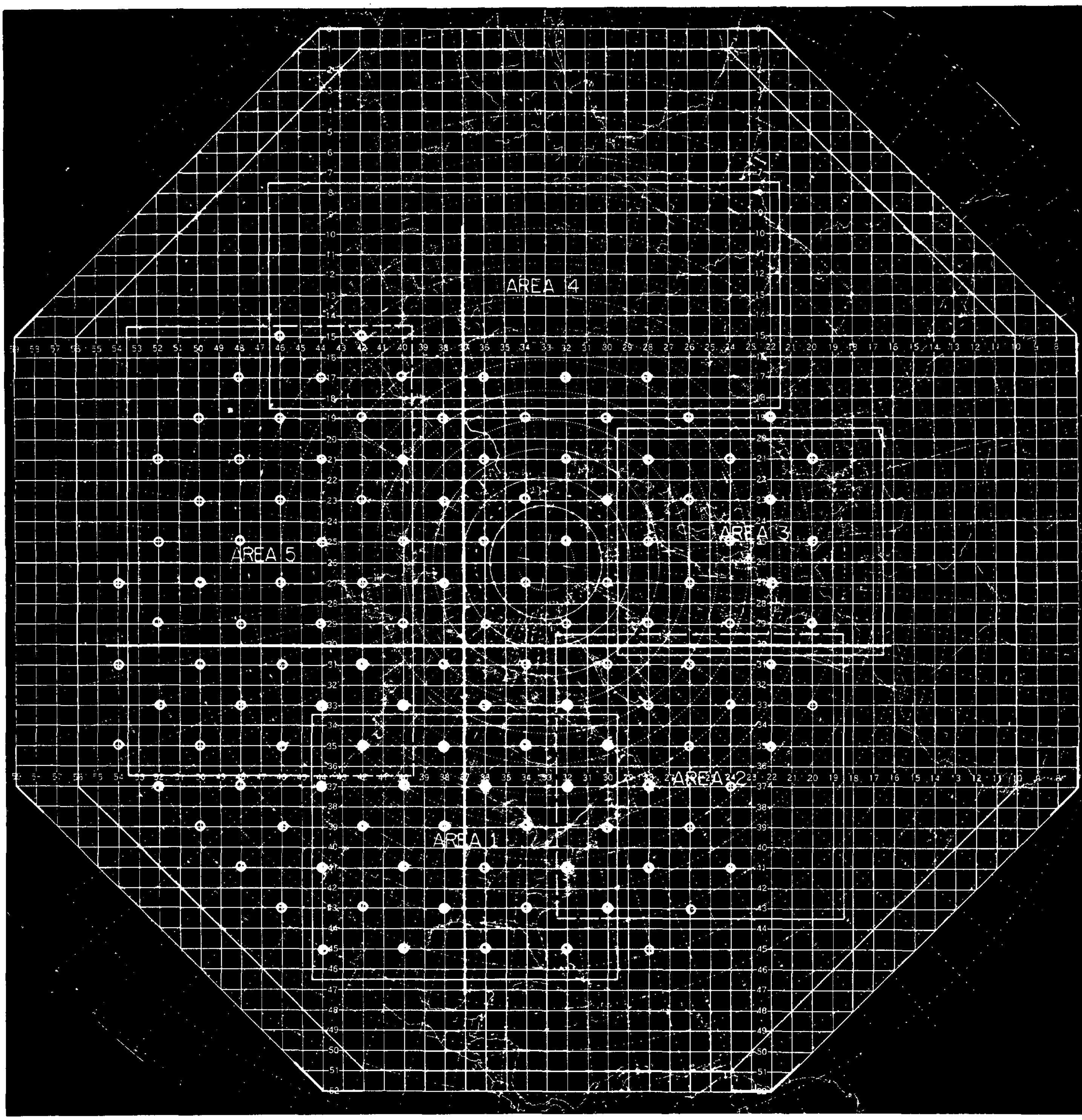

FIGURE 1.—NMC–NWP verification areas (forecast verifications by NWP Group, NMC, Suitland, Md.) showing circled grid points from which mean monthly 500-mb and error data were obtained to draw charts in figures 2–5 and 7–8.

7 and 8 to show the vertical distribution of PE error patterns from 1000–200 mb.

2. DISCUSSION OF VERY LARGE-SCALE ERROR PATTERNS

A visual inspection of the large-scale flow and error patterns in figures 2–5 indicates that in middle latitudes (35° N.–55° N.) wave numbers 3 and 4 predominate during winter and spring and that wave numbers 4 and 5 predominate in summer and fall. Before June 1966, when the three-level model was used at NMC, the large-scale error pattern was also characterized by a strong wave-number-1 component. The sign of the errors over Europe and Asia was predominantly negative, and over the re-

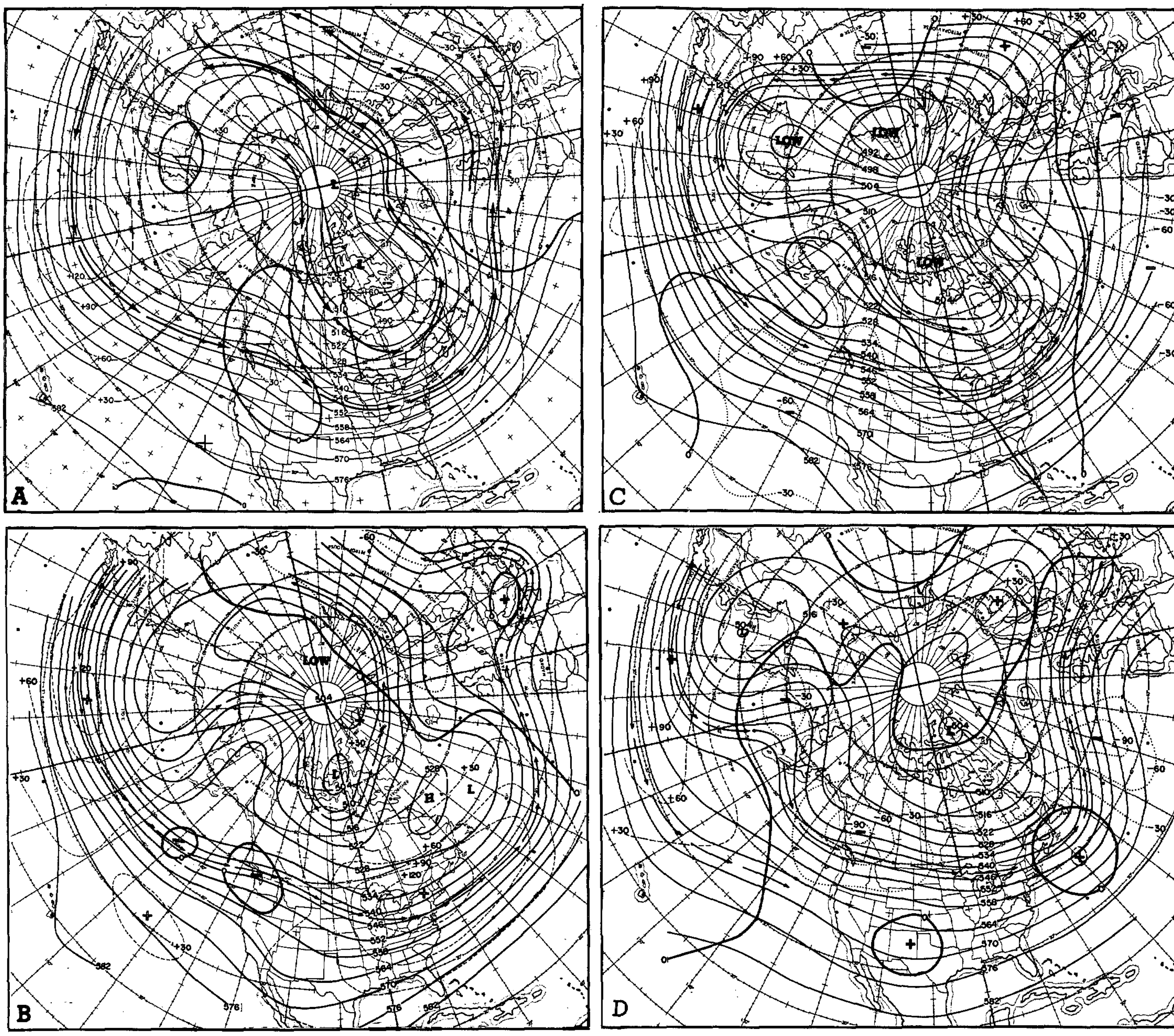

FIGURE 2.—Mean monthly observed 500-mb contours in decameters (solid lines) with mean observed jet-stream core positions (heavy arrows) and 36-hr three-level and PE 500-mb prognostic error patterns in whole meters (forecast minus observed 500-mb heights). Height and error data valid at 1200 GMT only are used for four months of January: (A) 1965, (B) 1966, (C) 1967, (D) 1968.

mainder of the hemisphere it was predominantly positive. For example, note January 1966 (fig. 2B) and July 1965 (fig. 4A).

After the introduction of the PE model in June 1966, the character of the large-scale errors changed somewhat. The most notable changes were 1) the increase in the amplitude of the monthly mean negative errors in ridges, particularly in the winter and spring, as can be seen by a comparison of figures 2B with 2C and 3B with 3C, from the eastern Pacific Ocean across North America and the Atlantic Ocean; 2) the persistence of a large negative error over the central and eastern Atlantic Ocean in all seasons except spring, where it was absent in 1967 and 1968 (figs. 3C and 3D); and 3) the absence in the PE 500-mb prognoses of the large three-level positive error over eastern North America (compare figs. 2B with 2C and 5B with 5C).

Several of these characteristic mean errors and their relations to daily error patterns will be discussed in more detail later in this paper. Little comment can be offered at this time on the reasons for the characteristic behavior of the models in forecasting waves 1 through 5. However, it is interesting to note the effect in the monthly charts of the changes in the characteristic error patterns after

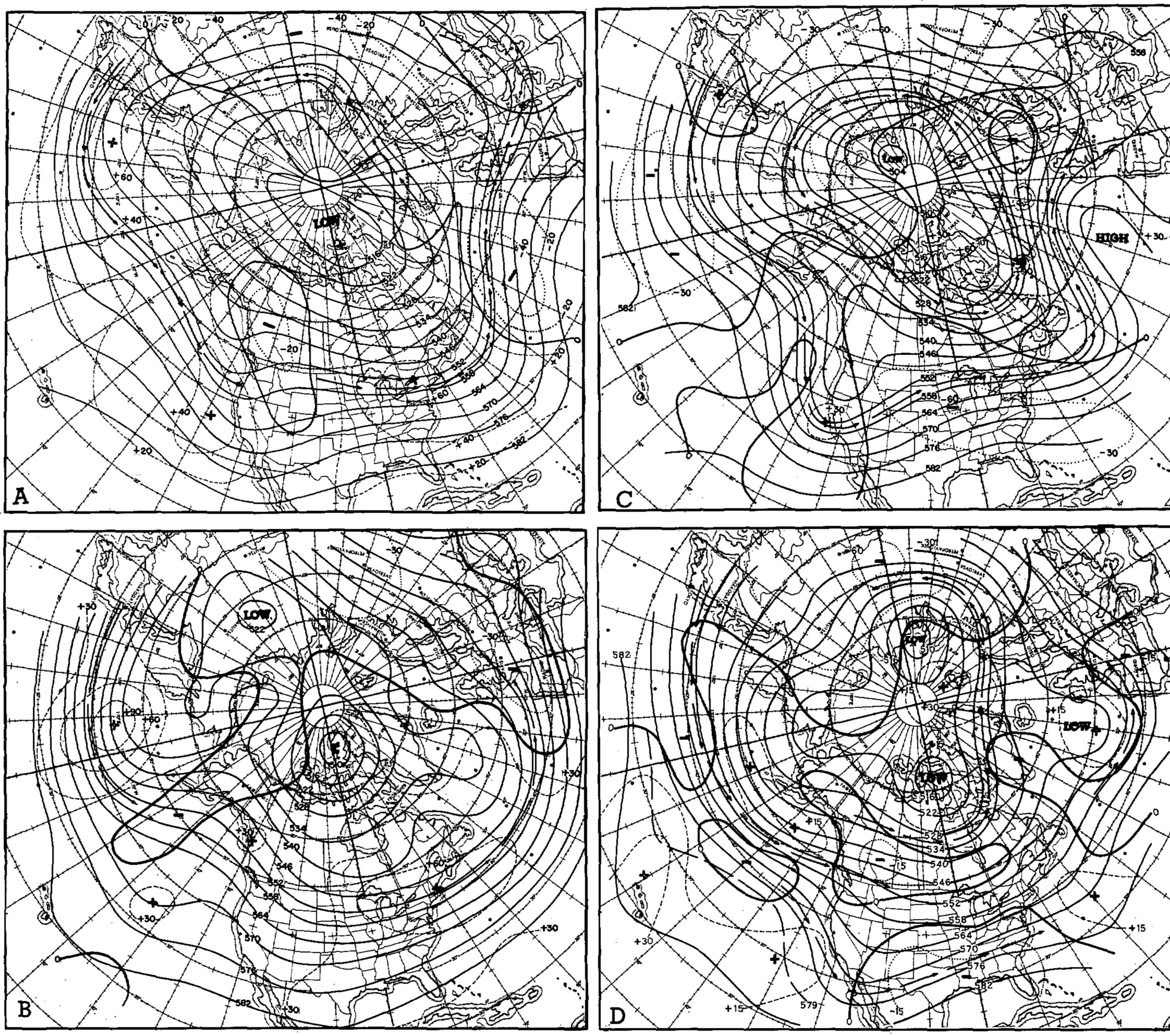

FIGURE 3.—Same as figure 2 for four months of April 1965–1968.

the introduction of the PE model. For instance, in the PE 500-mb prognoses, errors in wave numbers 3 and 4 appear to predominate largely because the large-scale negative errors in ridges around the entire hemisphere are a closer match in amplitude to the positive errors in troughs (compare figs. 2B and 2C). The large and persistent PE mean negative error over the Atlantic, unlike the three-level errors in this area, persists in troughs as well as ridges, although it tends to exhibit more amplitude in those months in which the mean circulation is dominated by a ridge (compare figs. 2C and 2D).

3. RELATION OF MONTHLY MEAN ERROR PATTERNS AND DAILY ERROR PATTERNS

Study of the large-scale errors and their relation to mean troughs, ridges, and jet-stream locations can be used to infer characteristic behavior of daily patterns. Necessary to a complete understanding of this relation is the study of the behavior of corresponding daily and mean monthly charts. A specific example of daily errors is given to show how they relate to large-scale mean errors.

In general, the relation between the location of mean errors and troughs and ridges remains constant from season to season and from year to year. In both baroclinic models, mean positive errors occur near the center of the mean troughs, usually north of the mean jet-stream positions.

Negative errors occur most frequently in mean ridges and characteristically have more amplitude and areal extent in the PE prognoses than the three-level prognoses, as has already been indicated in section 2. The relation of negative centers to the mean position of the

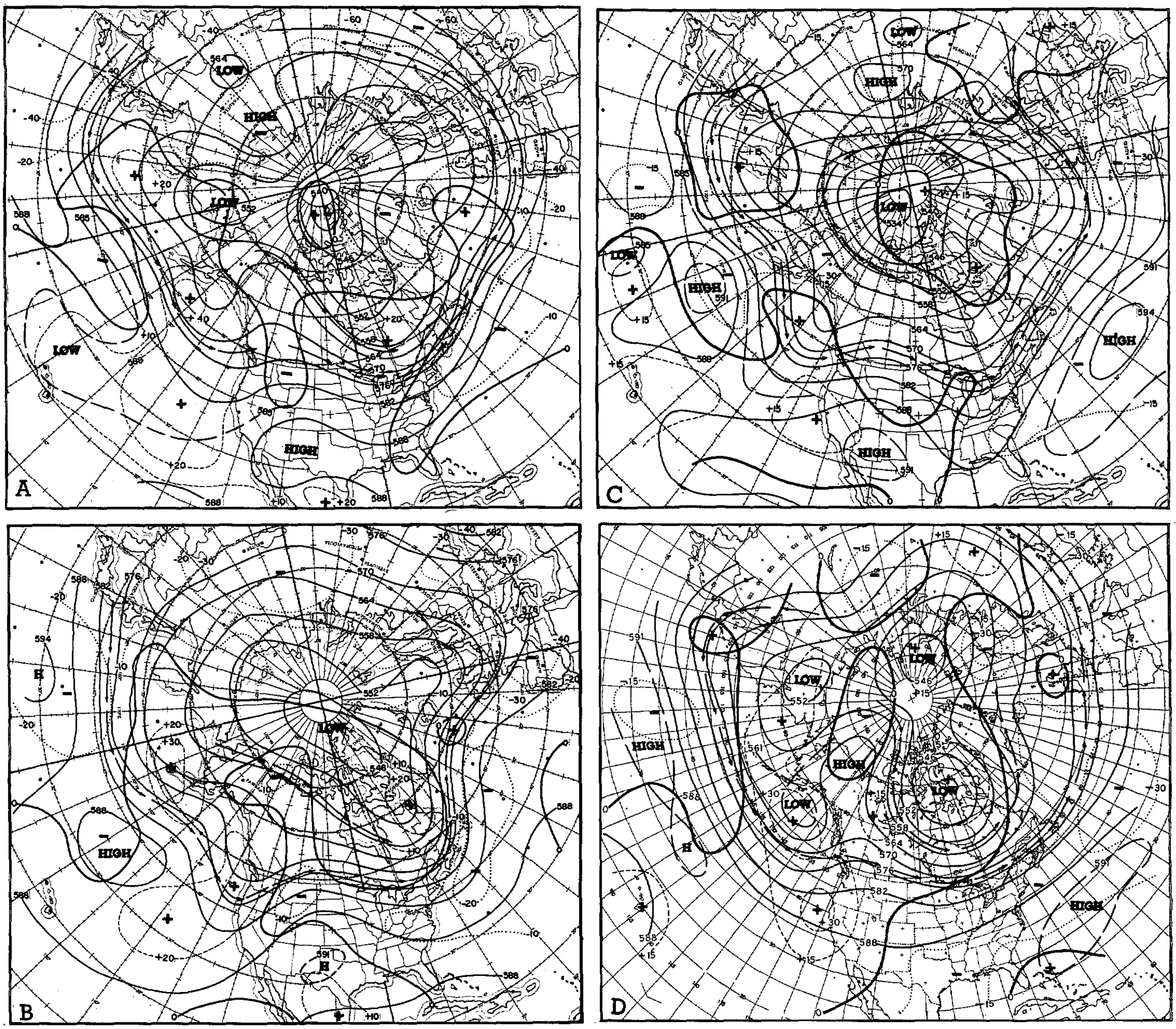

FIGURE 4.—Same as figure 2 for four months of July 1965–1968.

jet stream varies. However, the negative centers are more often found south of the mean position of the jet core.

Examination of daily error patterns shows good agreement with the structure of mean error patterns, namely: prognostic troughs and ridges normally lack amplitude in both the three-level and PE operational forecasts, or prognostic troughs contain positive errors and prognostic ridges contain negative errors. In both models, midtropospheric west winds are *underforecast* near and south of the jet in troughs and *overforecast* in the northern portion of troughs. Forecasts of individual 500-mb trough-ridge systems (i.e., short waves) typically suffer from two common defects, 1) slowness in translation and 2) lack of amplitude. For instance, in figure 6 note the error patterns with the two troughs along and off the Pacific coast of North America. The trough forecast to be 10° of longitude west of the Oregon-Washington coast lacks about 60 m of amplitude near its center. It is also about 5° of longitude slow, which accounts for most of the 160-m positive error over Vancouver Island. The 100-m error ahead of the closed Low over northern Arizona results more from slowness than from lack of amplitude in the PE prognosis. Both positive error centers are located near the center of the observed trough and just north of the *observed* jet core.

It is interesting to compare the individual day's error pattern in figure 6 with the corresponding mean error pattern in figure 8C. Note the similarity in the relations of error centers to ridges and troughs in the prognosis for 1200 GMT, Oct. 4, 1968 (fig. 6), and the mean 500-mb chart and error pattern for October 1968 (fig. 8C).

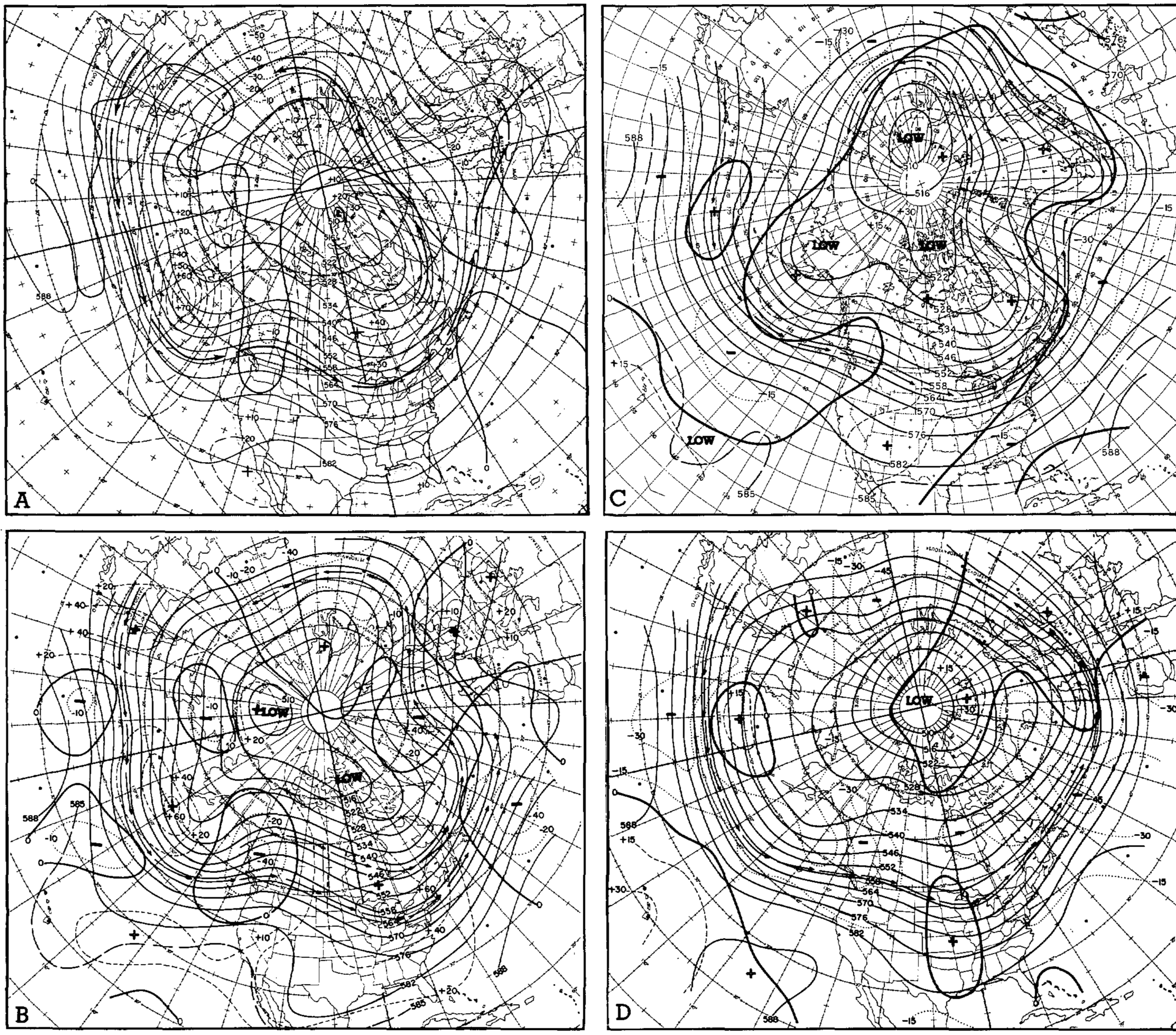

FIGURE 5.—Same as figure 2 for four months of October 1964–1967.

Examination of several months of mean and daily error patterns confirms the implications in the comparison of figures 6 and 8; namely: the mean patterns reflect the location and amplitude of the *predominant* errors that occur during each month and are not the heavily smoothed results of rapidly varying daily error patterns. Thus, one can infer systematic behavior of the daily errors in the model from examination of mean monthly errors.

WESTERN PACIFIC ERROR

The large positive error in the western Pacific dominates 500-mb prognoses in both the three-level and PE models. It appears in November when the mean position of the jet moves to or south of latitude 40° N. and disappears or weakens markedly by April as the mean position of the jet moves northward again across latitude 40° N. This error reflects the inability of both NMC operational baroclinic models to forecast the magnitude of the explosive cyclogeneses which regularly occur in the lower troposphere as 500-mb short waves move eastward from Asia into the western Pacific.

WESTERN NORTH AMERICAN ERROR

When a strong mean trough exists in the Gulf of Alaska, the negative error to its east over western Canada is larger than when a weak mean trough (or a mean ridge) exists over the Gulf of Alaska. This behavior has existed with both the NMC operational three-level and PE

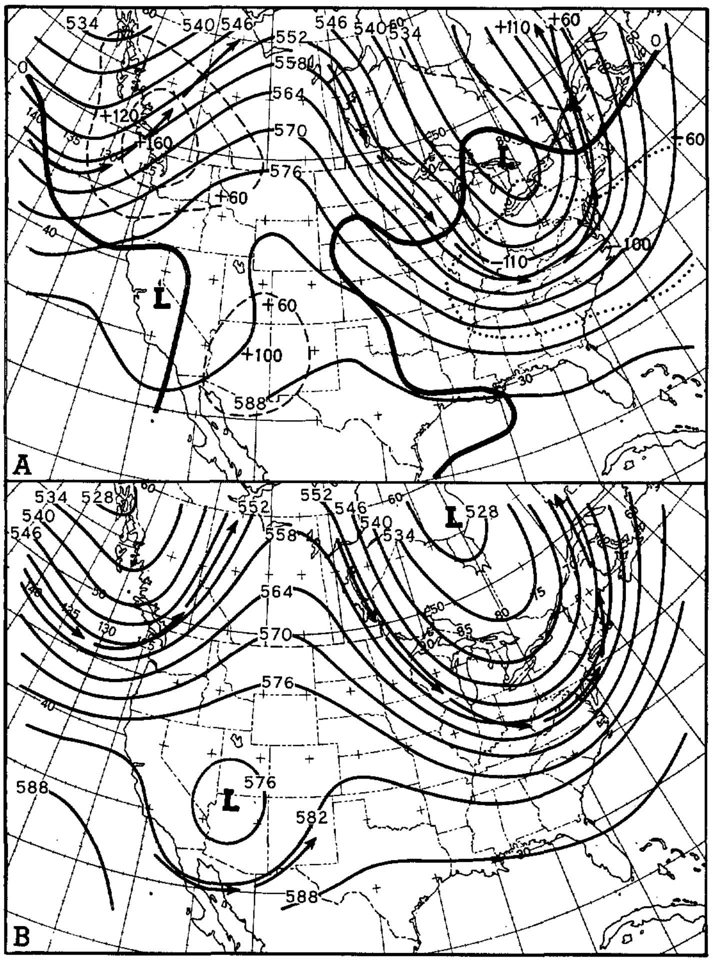

FIGURE 6.—(A) PE 36-hr 500-mb prognosis valid at 1200 GMT on Oct. 4, 1968, with contours in decameters and 36-hr PE errors (forecast minus observed) in meters; (B) 500-mb observed contours in decameters for 1200 GMT on Oct. 4, 1968. Jet-stream cores are shown by heavy solid arrows on both charts.

models. For instance: note the large negative error in western Canada with the strong Gulf of Alaska trough in January 1968 (fig. 2D) and October 1965 (fig. 5B). In January 1966 (fig. 2B) and October 1966 (fig. 5C), a weaker trough is accompanied by a weaker negative error. This error pattern has been very evident in daily 500-mb prognostic charts. It also has been accompanied in the PE model by a large negative bias in the sea-level prognoses over western Canada. Figure 9 shows an individual example of the behavior of this type of error on Jan. 18 and 19, 1968. The extensive negative error at 500 mb centered along the Pacific coast of Canada also shows up in the corresponding sea-level chart (compare figs. 9B and 9D).

This error has been diagnosed as resulting from the use in the model of heavily smoothed mountains over western North America. Higher mountains were introduced into the NMC operational PE model in September 1968 (Weather Analysis and Prediction Division, 1968). The mean 500-mb error pattern for October 1968, shown in figure 8C, is notable for the absence of the large negative "bull's eye" error in the ridge over western Canada upstream from the sharp Gulf of Alaska trough. Preliminary inspection of daily errors in the PE surface and 500-mb prognoses over the western United States during November and December 1968 indicates that the negative error over western Canada is occurring farther south over the United States with the roughened mountains. The amplification of the terrain in the American Rockies was not as large as that in the Canadian and Alaskan Rockies. Perhaps, forecast errors during the winter of 1968–69 will suggest the need for further adjustment in the model configuration of the American Rockies.

Figure 10 shows an individual case on Oct. 17 and 18, 1968, similar initially in synoptic situation over the Gulf of Alaska to figure 9. The improvement due to use of the roughened mountains is evident by comparing the 36-hr 500-mb negative error in western Canada in October 1968 (fig. 10C) with that in January 1968 (fig. 9A) when the smoothed mountains were used. The typical strong negative error centered on the western slopes of the Rockies is no longer present in the PE 500-mb prognoses. The weak negative error off the coast is due to slowness in the forecast eastward motion of the 500-mb trough. A more exact idea of the effect of rough versus smooth mountains in the same case can be seen by comparing the 36-hr 500-mb barotropic and PE prognoses in figures 10C and 10E.

The NMC operational barotropic mesh model (Gustafson, 1964) uses smoothed mountains and 850–500-mb prognostic wind shear to calculate vertical velocities due to terrain. Note that the greater difference between these two 36-hr 500-mb prognoses occurs over northwestern Canada where the height of the mountain ridge in the PE model has been increased as much as 800 m in elevation, as shown by comparing figures 11A and 11B.

EASTERN NORTH AMERICAN ERROR IN FALL, WINTER, AND SPRING

A mean trough has existed over eastern North America in the monthly series since 1965, although the April charts have shown a flat ridge displacing or flattening the southern end of this mean trough over the United States in three out of the 4 yr (fig. 3). Examination of the error patterns in this trough in the January, April, and October charts (figs. 2, 3, and 5) shows a remarkable change in structure of the error pattern after the introduction of the PE model. The large positive error in the middle of the trough near the jet core persisted in all three seasons in the three-level prognoses. In the PE prognoses, which first appear in the October 1966 chart of this series, the positive error has decreased in amplitude and withdrawn northward to the center of the mean Low usually located in northern Canada or over the polar basin. Over the eastern United States, the PE errors are weakly positive in January 1967 (fig. 2C) or even negative in October 1967 (fig. 5D). This dropoff in the amplitude of mean errors

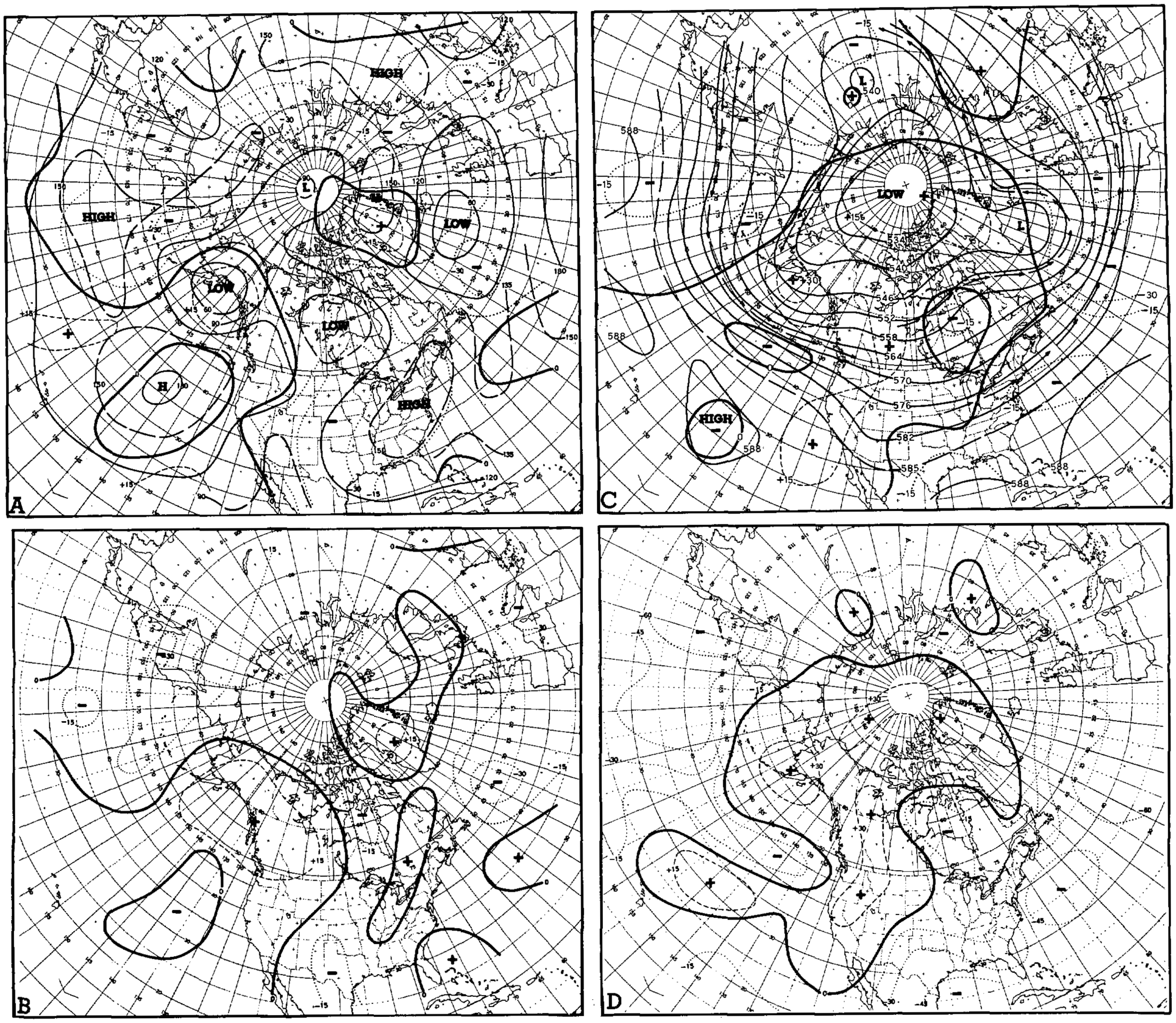

FIGURE 7.—(A) mean observed 1000-mb contours (valid at 1200 GMT only) and 36-hr prognostic 1000-mb errors in meters (forecast minus observed) for September 1968; (B) mean PE 36-hr prognostic 850-mb errors (1200 GMT only) in meters (forecast minus observed) for September 1968; (C) same as (A) for 500 mb; (D) same as (B) for 200 mb.

over eastern North America is quite remarkable since it occurs without any corresponding change in mean circulation. Also, notable in all seasons except summer is the dropoff in gradient of the errors over North America when PE prognoses are compared to three-level prognoses; for example, compare figures 5B and 5D.

Further evidence of the improvement of PE over three-level prognoses can be found in the NMC verification of 500-mb-height gradient forecasts over the Continental United States, using the S_1 score of Teweles and Wobus (1954). These are shown in figure 12. Here, the average skill of the PE 500-mb forecast (bar C) is about 10 percent better than the skill of the three-level 500-mb forecast (bar B).

However, this improvement in overall skill of performance does not mean that all forecast problems have been eliminated. The mean error charts show that, with the PE model, negative errors tend to predominate in the mean trough south of the jet with positive errors north of the jet—for example, in October 1966 and 1968 (figs. 5C and 8C) or January 1967 and April 1968 (figs. 2C and 3D). This configuration of a positive error north

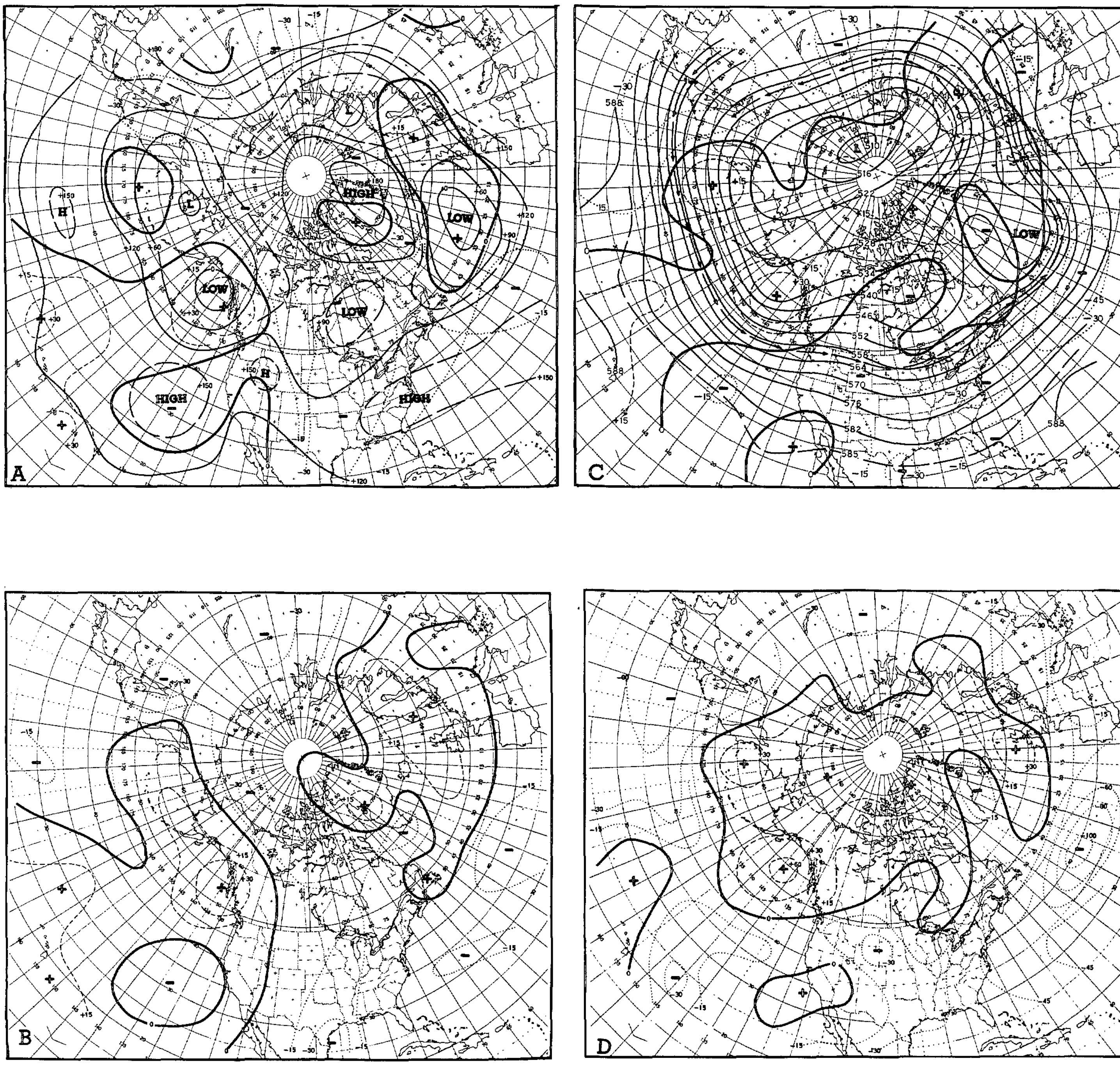

FIGURE 8.—Same as figure 7 for October 1968.

of a negative error represents, in the mean, one of the most serious errors in the daily prognoses for fall, winter, and spring. The *positive-north-of-negative couplet* shows up in the model when low-level cyclogenesis occurs in the real atmosphere. It signals the PE model's inability to occlude rapidly developing cyclones. Figure 10 shows an example of this error for the midwestern cyclogenesis of Oct. 17–18, 1968. The 500-mb error couplet in figure 10C results from the prognostic 500-mb Low lagging too far behind its observed position. In this P.E. forecast, the surface Low (fig. 10D) is moved rapidly northward *but* warms up during the period since the 500-mb Low does not catch up or occlude with the surface Low. In other words, the 1000–500-mb thickness over the surface Low *increases* in value during the forecast. Experiments at NMC with a wet and dry PE model indicate that the rapid movement and warmup of the surface Low is due to latent heat feedback in the model. Thus, the sea-level forecast is partially corrected by the latent heat feedback which warms up the lower troposphere but has little effect on the 500-mb prognosis. Even if some sort of truncation error control were introduced to speed up the movement of short waves in the PE forecasts, the basic problem of failure to occlude systems might remain in the model, since the problem is one of the 500-mb Low occluding or catching up with the surface Low. The PE

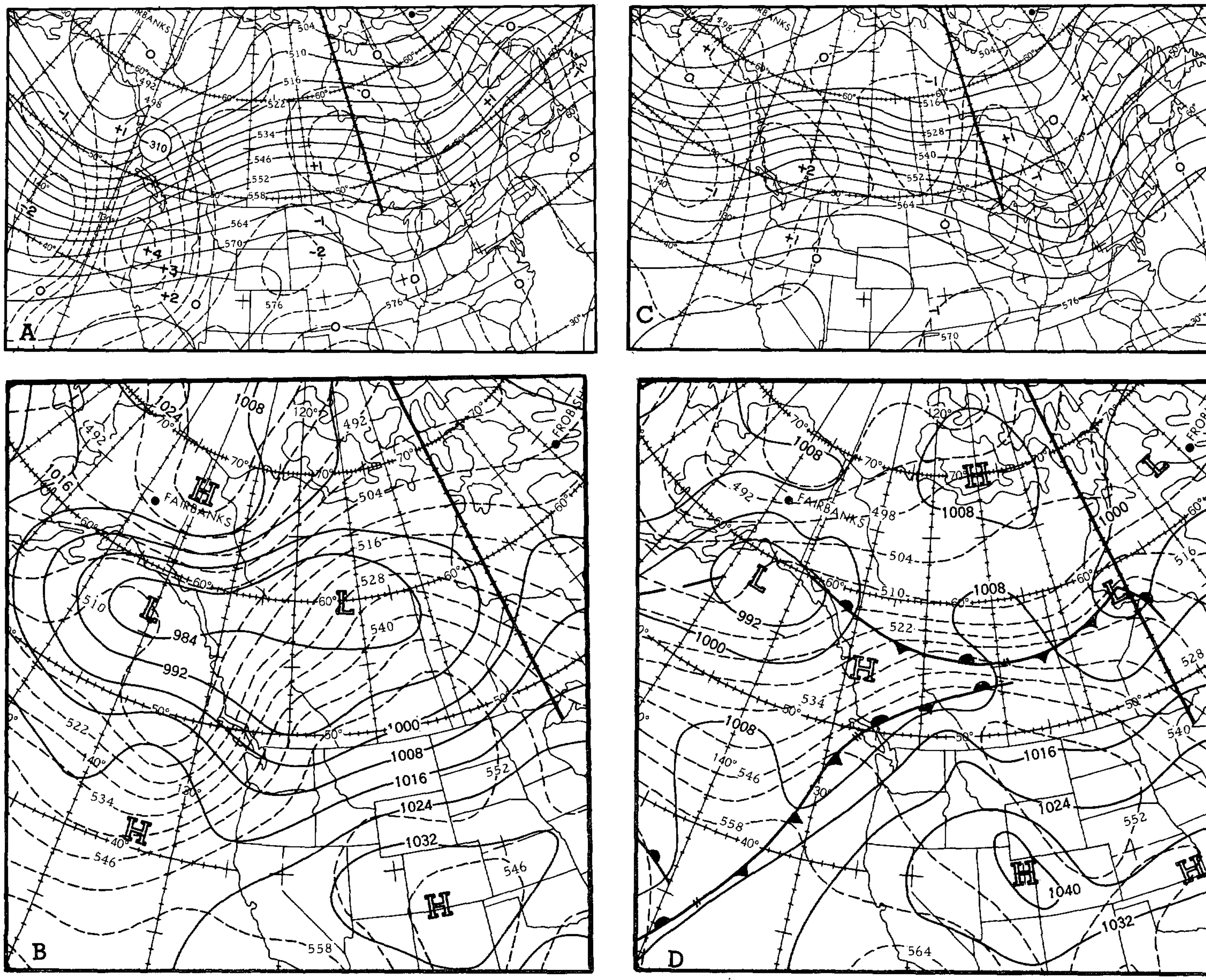

FIGURE 9.—(A) 36-hr PE 500-mb prognostic contours in decameters and 36-hr 700-mb vertical velocities in microbars per second, valid at 1200 GMT on Jan. 19, 1968; (B) 36-hr PE sea-level prognostic isobars in whole millibars and 36-hr prognostic 1000–500-mb-thickness contours (dashed) in decameters for 1200 GMT on Jan. 19, 1968; (C) observed 500-mb contours in decameters and 6-hr PE prognostic vertical velocities in microbars per second, valid at 1800 GMT on Jan. 19, 1968; (D) observed sea-level isobars in whole millibars, fronts and 1000–500-mb contours in decameters for 1200 GMT on Jan. 19, 1968.

layer-mean forecast of 90-percent relative humidity (fig. 10F) also lacks the typical comma or occluded shape which develops as the system occludes rapidly.

EASTERN NORTH AMERICAN ERROR IN SUMMER

Discussion of the July (summer) error patterns over eastern North America deserves separate consideration from the other three seasons because of their unique behavior. First, the large difference between three-level and PE error patterns over eastern North America does not show up in the summer. For instance, the mean flow and mean error patterns for July 1965 and 1966 (figs. 4A and 4B) are very similar in the area of concern. The PE model does have more error difference in the positive-negative error couplet from Labrador southeastward to Newfoundland. This error couplet reflects the systematic tendency in the daily charts for the PE prognostic 500-mb Lows to lag behind, or to the south of, the actual 500-mb Lows during surface cyclogenesis, which occurs most often in summer off the eastern Canadian coast. However, in general, one can conclude that there is little difference in the average performance of the two baroclinic models in summer over most of North America.

VERTICAL VARIATION OF ERROR PATTERNS

A preliminary evaluation of the vertical variation of mean error patterns is possible from inspection of figures 7 and 8 for September and October 1968. Two characteristics of the vertical variation of the PE mean monthly errors are noteworthy:

1) With increasing elevation, there is a slight increase in amplitude of mean positive errors near the center and a

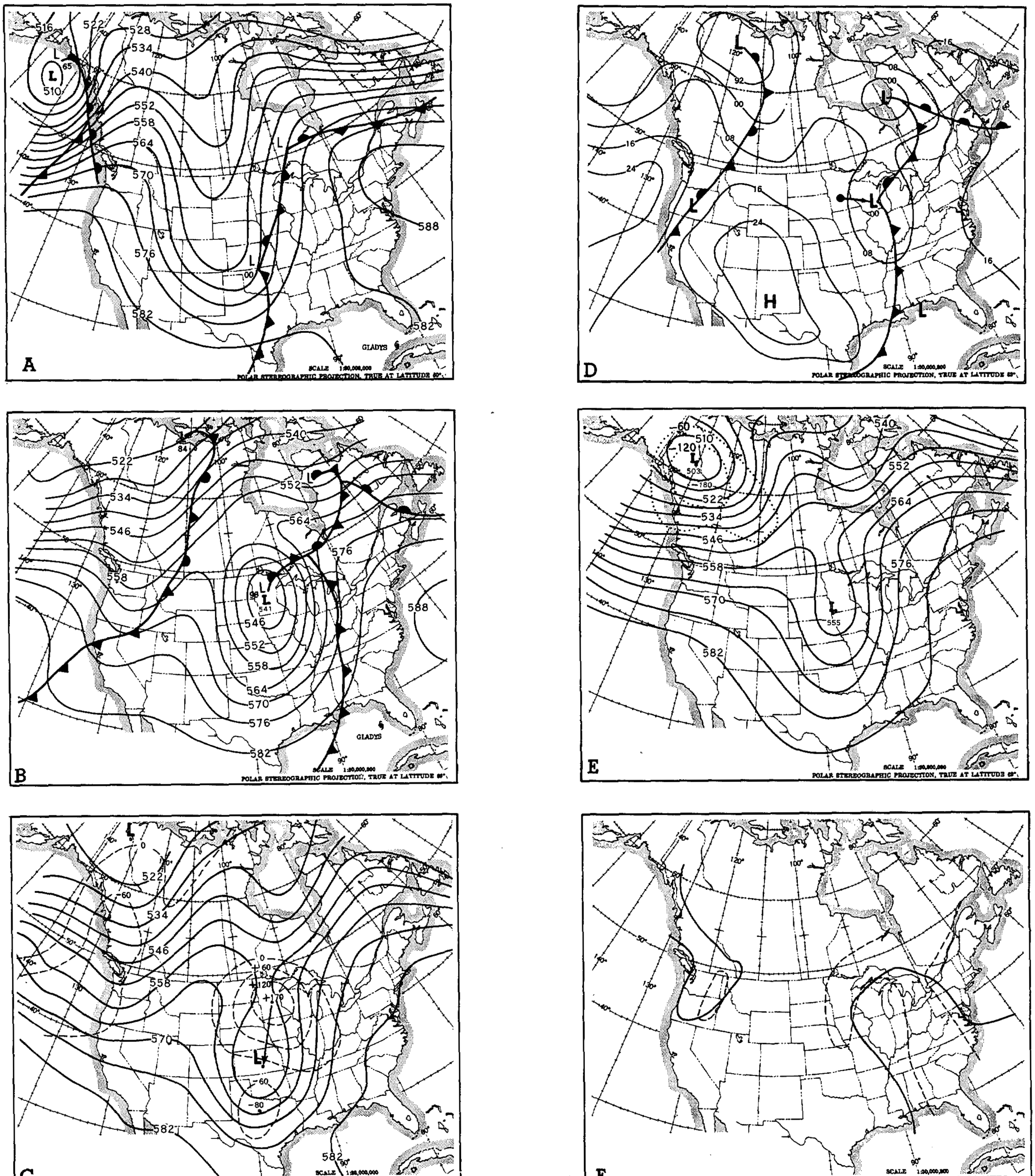

FIGURE 10.—(A) 500-mb contour analysis (decameters) and location of surface fronts and pressure centers (whole millibars hundred and thousands digit omitted) for 0000 GMT on Oct. 17, 1968; (B) same as (A) for 1200 GMT on Oct. 18, 1968; (C) 36-hr PE 500-mb prognosis in decameters with 36-hr 500-mb errors (forecast minus observed) in meters, valid at 1200 GMT on Oct. 18, 1968; heavy arrow indicates position error of 500-mb low center; (D) 36-hr PE sea-level prognosis, isobars in whole millibars (hundreds and thousands omitted) valid at 1200 GMT on Oct. 18, 1968; arrow indicates position error of sea-level low-pressure center; (E) barotropic 36-hr 500-mb prognosis valid at 1200 GMT on Oct. 18, 1968; dotted lines indicate error in prognosis over western Canada (forecast minus observed); (F) mean primitive equation precipitation (PEP) 1000–500-mb relative humidity prognosis (90-percent values shown by solid lines) and corresponding observed 72-percent 1000–500-mb mean relative humidity for 1200 GMT on Oct. 18, 1968.

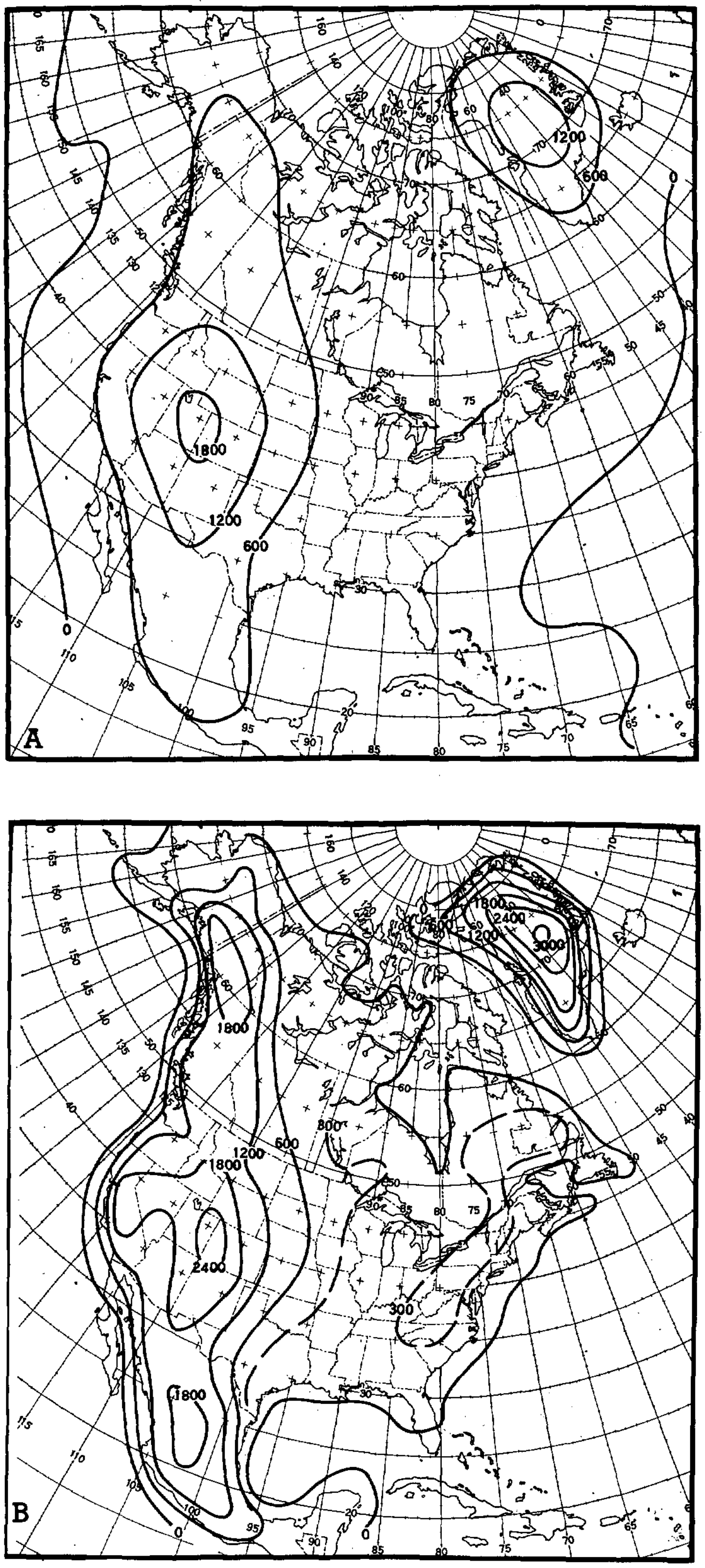

FIGURE 11.—(A) smoothed contours (in meters) of earth's elevation used in NMC PE model before September 1968; (B) augmented contours (in meters) of earth's elevation used in NMC PE model beginning in September 1968.

marked increase of negative errors around the periphery of the forecast area. This effect results in a net underforecast of the mean thermal wind from 1000–500 mb and from 500–200 mb. In other words, the mean west

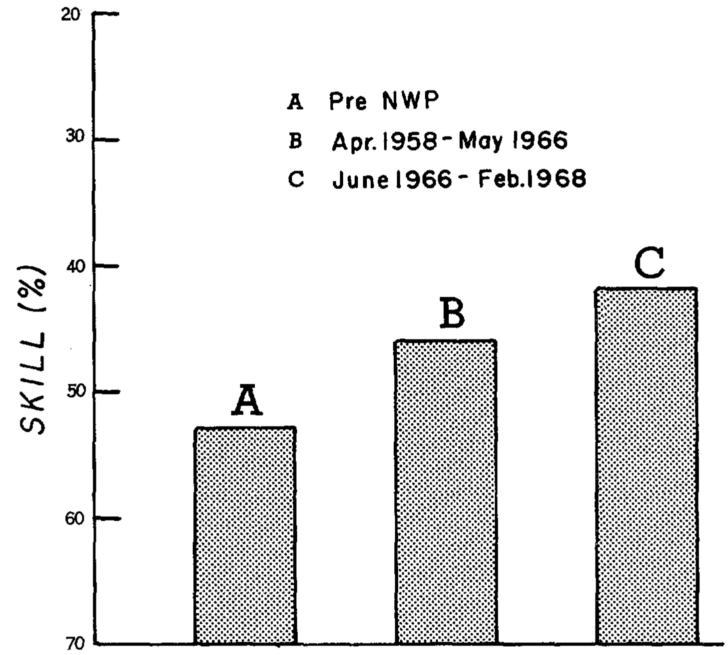

FIGURE 12.—Increase in skill of NMC 36-hr prognosis of 18,000 ft (500 mb) winds from the (A) pre-NWP period through use of (B) three-level and (C) PE operational forecast models. Skill is measured in terms of S_1 score (Teweles and Wobus, 1964) in which the lower score is the more skillful.

TABLE 1.—*Observed and forecast geostrophic winds for September and October 1968*

	RMSV geos. fcst.	RMSV geos. obsvd.	Percent difference (fcst.-obsvd.)
Sept. 1968	30.3 kt	31.8 kt	−5
Oct. 1968	34.8 kt	37.0 kt	−11

wind component is underforecast, particularly between 500 mb and 200 mb. Confirmation of this can be seen by comparing the root-mean-square-vector (RMSV) geostrophic wind at 300 mb, forecast by the PE model, with the RMSV geostrophic *observed* 300-mb wind (forecast verification by the NWP Group, NMC, Suitland, Md.).

Table 1 shows a comparison of the observed and forecast geostrophic winds for September and October 1968.

The daily wind forecasts derived from the PE prognoses in the middle and upper troposphere also systematically underforecast the strength of the winds in the vicinity of the core of the polar and subtropical jet streams. However, the source of this error is believed to be the inability of the model to resolve the strong wind shears in the vicinity of the jet core in the horizontal and vertical mesh used to make the forecast (i.e., 381-km, horizontal mesh length and approximately 5,000 ft to 15,000 ft between sigma surfaces in the vertical, Shuman, 1968).

TABLE 2.—*Mean error in 36-hr primitive equation sea-level pressure (forecast minus observed) at three points along latitude 40° N.*

	Point 1, 40° N.–90° W.	Point 2, 40° N.–100° W.	Point 3, 40° N.–110° W.
Sept. 1968	−5.2 mb	−3.9 mb	−2.7 mb
Oct. 1968	−4.9 mb	−4.0 mb	−4.3 mb

2) A mean 1000-mb trough exists from the northern Great Plains to the southern Rockies in September 1968 (fig. 7A). This trough moves eastward to the central Great Plains in October 1968 (fig. 8A). At 1000 mb, this trough is associated with a large negative error, centered ahead of the mean trough position. The extent and amplitude of this 1000-mb error decreases at 850 mb, 500 mb, and 200 mb *over the Plains* (figs. 7B–D and 8B–D). Examination of daily 36-hr pressure errors in the PE sea-level prognosis at three points along 40° N. latitude (shown in table 2) indicates that, in the mean, negative errors also occur in the sea-level pressures over the Plains.

Forecasters in NMC, using the PE sea-level prognoses, have also noted a systematic bias on the low side in PE prognostic sea-level pressures east of the Rockies. It is suspected that this negative error is due in part to differences between the observers' and the model's methods for reducing surface pressures to sea level, although much of the reduction problem was eliminated in 1967 through use of the "tendency method" in deriving sea-level prognoses from the PE forecasts (Weather Analysis and Prediction Division, 1967). For instance, introduction of the roughened terrain occurred in mid-September 1968 (Weather Analysis and Prediction Division, 1968). The terrain height at point 3 was increased by 600 m (compare fig. 11A with 11B), which may account in part for the September to October increase in sea-level pressure error at this point.

4. CONCLUDING REMARKS

Since 1964, hemispheric mean monthly 36-hr 500-mb height errors in NMC's operational baroclinic prognoses have shown a consistent pattern of positive errors in mean troughs and negative errors in mean ridges. These errors show up in the daily charts as a lack of amplitude in short-wave troughs and ridges and an underforecast of the strength of the polar jet core.

A comparison of the mean performance of the NMC three-level filtered model with the NMC primitive equation model shows that the greatest improvement in performance at 500 mb has occurred over the eastern two-thirds of North America. NMC's daily verification statistics over the United States showed some improvement in wind forecasts at 500 mb and substantial improvement in the sea-level prognoses (Shuman, 1968) after the PE model replaced the three-level model. Certain mean errors associated with fixed locations and/or geographical features have been noted. The consistent negative error in western Canada was diagnosed as a consequence of overly smoothed mountains. This error seems to have been eliminated over western Canada by introduction of "higher" mountains in September 1968. Certain very large-scale errors (e.g., in waves 1 through 5) seem to persist in 500-mb prognoses from both models. No explanation of the cause of these large-scale errors can be offered at this time. Vertical error distributions in PE prognoses, available since September 1968, show that the large-scale errors increase in amplitude with altitude.

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